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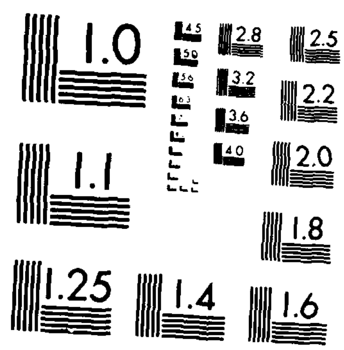

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Annual Report 10-1-85 to 9-30-86 #AFOSR-85-0269 Study of Infrared Nonlinear Processes in Semiconductors.

AD-A174 921

I. Research Objectives and Achievements

AFOSR-TR- 86-2211

This is the annual technical report for AFOSR Grant 85-0269, entitled "Study of Infrared Nonlinear Processes in Semiconductors". The primary aim of the program is to discover materials and/or structures with large, fast nonlinear optic susceptibilities. Such elements are required in optical signal processing systems, and for protection of imaging devices. The program is mainly experimental, with supporting theoretical work. Tests of nonlinear crystals also provide important information concerning carrier kinetics in semiconductors, through the difference frequency variation of $X^{(3)}$. In the past year, we have used this technique to determine carrier relaxation times, in the picosecond range, in n-Si :P and HgTe.

Where appropriate, we investigate the device implications of optical-semiconductor interactions. Our studies of free carrier, spin-induced Faraday rotation, ~~described below,~~ were motivated by the possibility of using this effect in tunable IR filters and CO_2 laser isolators.

II. Free Carrier, Spin-Induced Faraday Rotation in HgCdTe and HgMnTe

Electrons in narrow gap semiconductors have large g-values and strong spin-photon interactions. When their spins are aligned by a magnetic field ($\langle\sigma_z\rangle \neq 0$), this interaction causes Faraday rotation, whose Verdet constant has a sharp resonance when the optical energy approaches the band gap. Thus, the process can be used as a band pass filter to select near-gap radiation.

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

1.) Demonstrated large, resonant, spin-induced, free carrier Faraday rotation in n-HgCdTe and n-HgMnTe. The effect may be useful in filters, limiters, and laser isolators.

2.) Measured nonlinear optical susceptibility, $\chi^{(3)} = 10^{-4}$esu, in HgTe epilayer. This is the largest nonlinearity known with picosecond speed.

3.) Studied impurity-induced nonlinearity in n-Si.

4.) Demonstrated that resonant levels can cause differential negative resistance.

5.) Proved that instabilities enhance optical nonlinearities.

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We have studied spin-induced Faraday rotation of CO_2 laser radiation, at 2 K, in n-HgCdTe and n-HgMnTe crystals with E_G = 110-130 meV. The Verdet constant, at resonance, in an n-HgCdTe sample containing 10^{15} electrons/cc. is 0.19 degree/cm-G. This value is ten times larger than that expected from interband Faraday rotation, and two orders of magnitude larger than the free carrier plasma effect. The Verdet constant decreases with laser intensity.

The maximum Verdet constant in a lightly doped HgMnTe crystal is 1.8 degree/cm-G. This value exceeds that predicted theoretically by a factor of five.

In both HgCdTe and HgMnTe, the Faraday rotation rapidly decreases as the light is tuned away from the band edge. In one case, the rotation at 10.6 μ is only 25% that at 9.5 μ.

The resonant Faraday effect may find application in laser isolators or tunable infrared filters. We are interacting with Lincoln Laboratory engineers concerning these possibilities. High quality HgCdTe crystals were provided by Dr. D. Nelson of Honeywell. This work will be presented at the 1986 MCT Workshop in Dallas.

III. Optical Nonlinearity of Zero Gap Semiconductors

We have recently measured a room temperature $\chi^{(3)} \approx 10^{-4}$ esu, with picosecond response time, in a HgTe epilayer. To our knowledge, this is the largest nonlinear optic susceptibility, with picosecond speed, ever observed; the previous record, by Yuen, was $\chi^{(3)}$ = 8×10^{-6} esu in p-HgCdTe. The HgTe experiments were performed with finite-difference-frequency and degenerate four wave mixing. In the former, $\chi^{(3)}$ varied as $(\Delta\omega)^{-2}$ to the lowest difference frequency, $\Delta\omega = \omega_1 - \omega_2 = 1.38$ cm^{-1}, attainable with our CO_2 lasers.

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The $\chi^{(3)}$ determined from degenerate four wave mixing was comparable to that at $\Delta\omega = 1.38\ cm^{-1}$. These results imply that the nonlinear process has a relaxation time of $\approx$ 5 psec.

We believe that electron-hole generation, via transitions between the degenerate Γ_8 bands, is responsible for the nonlinearity of HgTe. The effect is magnified by the large interband absorption coefficient ($\alpha \approx 3000\ cm^{-1}$). Absorption may preclude bistability via this mechanism, but the process should prove useful in applications requiring transient gratings. In this regard, it is important that the four wave power varies as the cube of the pump powers, $P_3 \propto P_1{}^2 P_2$, to our highest pump power ($1 MW/cm^2$). The linear absorption at 10.6 μ also shows no evidence of saturation below $1 MW/cm^2$.

The nonlinearity may be enhanced by matching the ($\Gamma_8 - \Gamma_6$) splitting to the laser energy. At 10.6 μ this condition requires ($Hg_{0.94} Cd_{0.06}$)Te or ($Hg_{0.97} Mn_{0.03}$)Te crystals. The $\Delta\omega \rightarrow 0$ limit of $\chi^{(3)}$ is determined by the recombination time, which might be increased by splitting the Γ_8 degeneracy with strain or magnetic field; HgMnTe is favorable for the latter.

Professor J. Schetzina, of N.C. State University, provided HgTe epilayers for this work. We anticipate a continuing collaboration.

IV. Nonlinear Optics near the Metal-Insulator Transition

Our studies of carrier-induced, optical nonlinearities in Si are continuing. Last year we showed that the nonlinear susceptibility of n-Si :P is enhanced near the metal-insulator transition ($n \approx 4 \times 10^{18}/cc$). Those measurements have recently been extended into the $n > 10^{19}/cc$. range in Si-on-insulator samples provided by Dr. L. Pfeiffer of A.T. & T. Bell Laboratories. The new experiments show that $\chi^{(3)}$, per carrier, is constant above $n = 10^{18}$/cc.

We plan to continue nonlinear optic experiments with Si-on insulator samples. These structures are much easier to work with than bulk Si crystals because they are 1-2 μ thick (ideal for nonlinear optics experiments), whereas extensive, difficult polishing of bulk crystals is required to achieve such dimensions. Moreover, Si-on-insulator can easily be doped or damaged with ion implantation. The theory of the nonlinearity shows that it is proportional to the carrier density at impurity sites. Thus, we are anxious to vary this quantity with different dopants (n-type vs. p-type, deep vs. shallow, etc.) and different damage levels.

V. Nonlinearities due to Resonant Levels

The optical nonlinearity of n-Si :P is caused by electron-impurity interactions. That experiment, to our knowledge, is the first demonstration of an optical nonlinearity caused by scattering; other free-carrier-induced optical nonlinearities result from special features of the band structure. Since $\chi^{(3)}$ is proportional to the energy (or temperature) derivative of the nonlinear interaction, it is natural to consider the possibility of inducing nonlinearity (both dc and optical) with resonant scattering levels near semiconductor band edges. Resonances occur in GaAs/(Ga,Al)As superlattices step-back doped with deep donors such as Si, and in the diluted magnetic semiconductor crystal $(Hg_{0.65}\ Cd_{0.35})$ Se : Fe. Our calculations show that such materials can have negative differential conductivity of the S-shaped type. In the superlattice case, the energy and width of the resonant level can be controlled by varying the barrier layer composition and the step-back distance.

Further theoretical studies of the dc nonlinearities are planned; we will also investigate the effect of resonant levels on optical nonlinearities. Experiments to test these ideas are in progress. Drs. A. Mycielski (Warsaw) and J. Furdyna (Purdue) have provided HgCdSe : Fe samples. The Bell Labs. group of Dr. D. Chemla may grow GaAs/(Ga,Al)As : Si superlattices for these studies. In the latter, transverse electric fields can be used to vary the electron-resonant level coupling, and thus modulate the conductivity.

VI. Instability-Enhanced Optical Nonlinearities

In n-Si :P there is an enhancement of $\chi^{(3)}$ near the metal-insulator transition. This observation leads to the question: "Are optical nonlinearities enhanced at other phase transitions or at electrical instabilities?" We have shown theoretically that, at the threshold for transport instabilities of the S-shape type (switching instabilities), the low frequency ($\Delta\omega \to 0$) nonlinear optic susceptibility of such a system diverges. Further calculations, to explore the frequency variation of the enhancement are planned. The idea will be tested with nonlinear optic experiments at the threshold of the well known avalanche breakdown instability in cold n-Ge or n-Si.

VII. Publications

[1] P.A. Wolff, S.Y. Yuen, and G.A. Thomas, "Nonlinear Optics Near the Metal Insulator Transition", Solid State Comm. (to be published).

[2] S.Y. Yuen, P.A. Wolff, P. Becla, and D. Nelson, "Free Carrier, Spin-Induced Faraday Rotation in HgCdTe and HgMnTe", Procs. of 1986 MCT Workshop (to be published).

[3] S.Y. Yuen, P.A. Wolff, and J. Schetzina, "Optical Non linearity in HgTe", (to be published).

[4]J. Stark and P.A. Wolff, "Transport Nonlinearities Caused by Resonant Scattering", (to be published).

[5]Ralph A. Hopfel, Jagdeep Shah, Peter A. Wolff, and Arthur C. Gossard, "Negative Absolute Mobility of Minority Electrons in GaAs Quantum Wells", Phys. Rev. Lett. 56, 2736 (1986).

VIII. Thesis

"Magnetic Polarons in Semimagnetic Semiconductors - a Time-Resolved Photoluminescence Study of Exciton-Magnetic Polaron Complexes in Cd_{1-x} Mn_x Se and Cd_{1-x} Mn_x Te",
John J. Zayhowski, PhD Thesis in Electrical Engineering and Computer Science, MIT, February 1986.

IX. Personnel

Prof. P.A. Wolff, Principal Investigator
Dr. S.Y. Yuen, Co-Principal Investigator
Prof. L.R. Ram-Mohan, Consultant
E. Isaacs, Physics Graduate Student
C. McIntyre, Physics Graduate Student
J. Stark, Physics Graduate Student
S. Wong, Physics Graduate Student
J. Zayhowski, Electrical Engineering and Computer Science Graduate Student

X. Interactions

We have a continuing interaction with A.T. & T. Bell Laboratories through Professor Wolff's consulting contract. Dr. G.A. Thomas, of Bell, provided samples and was a co-author in our paper on optical nonlinearities in n-Si. To continue this work, Dr. L. Pfeiffer (also of Bell) is providing Si-on-insulator structures. One of our students, J. Stark, spent the summer of 1986 at Bell Laboratories, Holmdel, fabricating structures for high field transport measurements in (HgCd) Se : Fe. His research, on nonlinear transport in GaAs/(Ga,Al)As : Si superlattices, will continue under the joint supervision of Professor Wolff and Dr. D. Chemla (Bell Labs, Holmdel).

We collaborate with the Honeywell Electro-Optics Group (Lexington, MA) in experiments requiring HgCdTe. Drs. M. Reine and D. Nelson have been very helpful in providing high quality crystals.

The zero gap (HgTe) work is collaborative with Prof. J. Schetzina (N.C. State University). Ultimately, we hope that he will provide us (HgCd)Te epilayers and HgTe/CdTe superlattices to optimize the zero gap nonlinearities.

At MIT we interact regularly with Dr. P. Becla and Professor A. Witt regarding growth and characterization of semiconductor crystals. We also discuss nonlinear optical processes and devices with Profs. E. Ippen and H. Haus.

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